REMARKS

The applicant has had an opportunity to carefully consider the Patent and Trademark Office's (PTO's) Office Action of June 16, 2005 and believes this amendment is fully responsive to every point raised by the Examiner. Reconsideration is respectfully requested of the rejections and objections concerning this application. Claims 1-36 remain in the application in original form after this paper is entered.

THE OFFICE ACTION

Claims 1-36 stand rejected under 35 U.S.C. §102(a) as being anticipated by Parvez, Shahid and Zhiqiang Gao, A Novel Controller Based on Multi-Resolution Decomposition Using Wavelet Transforms (Parvez and Gao Paper).

The undersigned called Examiner Kasenge in August 2005 regarding the above rejection. The applicants and the undersigned thank the Examiner for the many courtesies extended during that telephone conversation. During the telephone call, the authorship of the Parvez and Gao Paper and the inventorship of the application were discussed. It was agreed that a response to the rejection could identify common authorship and inventorship and provide evidence of first publication of the Parvez and Gao Paper.

THE ART REJECTIONS

Parvez and Gao Paper is Disqualified as a Reference.

As reflected on the Filing Receipt mailed December 23, 2003 and other papers of record, Zhiqiang Gao and Shahid Parvez are named as applicants/inventors with regard to the above-identified patent application. In rejecting claims 1-36 under 35 U.S.C. §102(a), the PTO has relied upon the Parvez and Gao Paper. The authors of the Parvez and Gao Paper are Shahid Parvez and Zhiqiang Gao. The authors of the Parvez and Gao Paper are the same as the applicants/inventors of the patent application. Therefore, the applicants respectfully submit that the invention was NOT described in the Parvez and Gao Paper before the invention thereof by the applicants. Accordingly, the applicants respectfully submit that the Parvez and Gao Paper is disqualified as a 35 U.S.C. §102(a) reference and request that the PTO withdraw the rejection of claims 1-36 relying on the Parvez and Gao Paper.

Additionally, the applicants submit that the Parvez and Gao Paper was first published less than one year prior to the filing date of the above-identified application. A Parvez and Gao Paper published by the Instrumentation, Systems, and Automation (ISA) Society and information released by ISA concerning ISA 2002 is attached as an Appendix to provide evidence of first publication after October 1, 2002. As shown by the Appendix, the Parvez and Gao Paper was published in conjunction with ISA 2002 which was held October 21-24, 2002 in Chicago, Illinois.

CONCLUSION

For the reasons detailed above, it is respectfully submitted that all claims in the application (Claims 1-36) are now in condition for allowance and an indication to that effect is earnestly solicited. Furthermore, if the Examiner believes that additional discussions or information might advance the prosecution of this case, the Examiner should feel free to contact the undersigned at the telephone number indicated below.

Respectfully submitted,

16 September 2005

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Analysis Division

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Process Measurement and Control Division

Robotics and Expert Systems Division

A NOVEL CONTROLLER BASED ON MULTI-RESOLUTION DECOMPOSITION USING WAVELET TRANSFORMS

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ABSTRACT

In this paper, a Wavelet Controller analogous to a Proportional-Integral-Derivative controller is proposed. The control strategy is based on the multi-resolution decomposition of error signal using Wavelet Transforms. The output from a system represents the cumulative effect of many underlying phenomena such as process dynamics, measurement noise, effects of external disturbances etc., which manifest on different scales. The wavelet decomposition, which represents the error signal at different scales, enables us to compensate for these uncertainties in the control design. Simulation results are shown to validate the control strategy.

1. INTRODUCTION

A novel control strategy based on the multi-resolution decomposition of signals using Wavelet Transforms is proposed. Wavelets have a tremendous impact on a number of modern disciplines, but they have been mostly used for signal and image analysis. Wavelets possess two properties that make them especially valuable for data analysis: they reveal local properties of the data and they allow multi-scale analysis. Their locality is useful for applications that require online response to changes, such as controlling a process. Recently some work has been reported on use of time-frequency localization of wavelet transforms in process control industry [1, 3, 4]. In this paper we propose a Wavelet Controller (WC) analogous to a Proportional-Integral-Derivative (PID) controller.

A PID controller is widely used across the industry. It is easy to implement and relatively simple to tune. In general, a PID controller takes as its input the error (e), acts on the error so that a control output (u) is generated. Similarly a Wavelet Controller decomposes the error signal into its high, low and intermediate frequency components, using the multi-resolution decomposition property of the wavelets. Each of these components are scaled by their respective gains, and then added together to generate the control signal u. The output from a system represents the cumulative effect of many underlying phenomena such as process dynamics, measurement noise, effects of external disturbances etc., which manifest on different scales. The wavelet decomposition, which represents the error signal at different scales, enables us to compensate for these uncertainties dynamically in the controller.

In Section 2, a brief description of wavelet transforms and multi-resolution decomposition is given. The framework of a Wavelet Controller is discussed in Section 3. Extensive simulations have shown that the controller works well on different types of plants. Simulation results on a motion control plant and a temperature regulation plant are shown in Section 4. Finally, some concluding remarks are included in Section 5.

2. WAVELETS AND MULTI-RESOLUTION DECOMPOSITION

Multi-resolution analysis is a convenient framework for hierarchical representation of functions or signals on different scales. The basic idea of multi-resolution analysis is to represent a function as a limit of successive approximations. Each of these successive approximations is a smoother version of the original function with more and more of the finer "details" added. Wavelets are terminating basis vectors used to decompose signals into a set of coefficients. Consider a continuous signal, $f(t)$, and generate the following sequence of approximations [2],

$$f^m(t) = \sum_{n=-\infty}^{\infty} f_{m,n}\phi(2^m t - n)_{m=0,1,2,\ldots} \qquad (1)$$

Each approximation is expressed as the weighted sum of the shifted versions of the same function, $\phi(\tau)$, which is called the scaling function. If the $(m+1)$th approximations is required to be a refinement of the mth approximation, then the function $\phi(2^m t)$, should be a linear combination of the basis functions spanning the space of the $(m+1)$th approximation, i.e.

$$\phi(2^m t) = \sum_k h(k)\phi(2^{m+1}t - k) \qquad (2)$$

If $V^{(m+1)}$ represents the space of all functions spanned by the orthogonal set, $\{\phi(2^{(m+1)}t - k);\ k \in Z$, the set of integers$\}$, and $V^{(m)}$ the space of the coarser functions spanned by the orthogonal set, $\{\phi(2^{(m)}t - p);\ p \in Z\}$ then $V^{(m)} \subset V^{(m+1)}$. Let

$$V^{(m+1)} = V^{(m)} \oplus W^{(m)}, \qquad (3)$$

then, $W^{(m)}$, is the space that contains the information added upon moving from the coarser, $f^{(m)}t$, to the finer, $f^{(m+1)}(t)$, representation of the original function, $f(t)$. Mallat[2] shows that there are spaces, $W^{(m)}$ that are spanned by the orthogonal translates of a single function, $\psi(2^{(m)}t)$, thus leading to the following equation

$$f^{(m+1)}(t) = f^{m}(t) + \sum_{n=-\infty}^{\infty} f_{m,n}\psi(2^{m}t - n) \qquad (4)$$

The function, $\psi(2^{(m)}t)$, is called a wavelet and is related to the scaling function $\phi(2^{(m+1)}t)$, through the following relationship

$$\psi(2^{m}t) = \sum_{k} g(k)\phi(2^{m+1}t - k) \qquad (5)$$

$h(k)$ and $g(k)$ from a conjugate mirror filter pair. Summarizing the discussion a wavelet series representation of the signal f(t) is given by

$$f(t) = \sum_{k=-\infty}^{\infty} c_{j_0,k}\phi(t) + \sum_{j=j_0}^{\infty}\sum_{k=-\infty}^{\infty} d_{j,k}\psi_{j,k}(t)$$

$$c_{j,k} = \int f(t)\phi_{j,k}(t)dt \qquad (6)$$

$$d_{j,k} = \int f(t)\psi_{j,k}(t)dt$$

Thus a wavelet transform decomposes a signal $f(t)$ into trend (c) and detail coefficients (d) as given in Eq. (6). The first step in decomposition consists of computing the trend and detail coefficients. Thereafter, the trend coefficients combined with the scaling function as a basis is used to regenerate the trend signal (left side of the summation in Eq. (6)) and detail coefficients using the wavelets as a basis is used to regenerate the detail signal (right side of the summation in Eq. 6). The trend signal captures the high scale (low frequency) information and detail signal captures the low scale (high frequency) information contained in the signal $f(t)$. Depending upon the number of decomposition levels the end product of a multi-resolution decomposition is a set of these signals at different scales (frequencies). For example, if a 3-level decomposition of error signal is done, it results in one trend signal (low frequency) and three detail signals (high and intermediate frequency). There is redundancy in the trend signal hence only one obtained at the last level is chosen. The frequency information of these decomposed signals is approximate since wavelet doesn't have a precise frequency like sines and cosines of Fourier analysis.

3. WAVELET CONTROLLER

Most control applications in industries still rely on a traditional PID controller. PID have been a phenomenon in industry die to their intuitiveness and simplicity of tuning. In general, a PID controller takes as its input the error, e, then acts on the error so that a control output, u, is generated. Gains Kp, Ki and Kd are the Proportional, Integral and Derivative gains used by the system to act on the error, integral of the error, and derivative of the error respectively. In terms of frequency information the proportional and integral terms tend to capture the low frequency information of the error signal and derivative captures the high frequency information of the signal. In a similar manner a WC decomposes the error signal into its high, low and intermediate frequency components, using the multi-resolution decomposition property of the wavelets discussed in Section 2. Each of these components are scaled by their respective gains, and then added together to generate the control signal u.

Unlike a PID controller, which has three tuning parameters (gains) a WC can have two or more parameters based on the level of decomposition of the error signal. For example, a one-level decomposition yields a low and a high-frequency component. So a controller with a one-level decomposition will have two gains. In order to capture more information if a two-level decomposition is done on the error signal, we end up with three frequency components. Each of these components can be scaled by gain and added to generate the control signal. A schematic diagram of a plant using WC is shown in Fig. 1. Since there are a number of different wavelets, choice of a wavelet affects the performance of the controller. In general there are two kinds of choices to make: the system of representation (continuous, discrete) and the properties of the wavelets themselves: for example, the number of degree of regularity. A common theme in choice is trade off. If you want more resolution in frequency, you get less in time; if you want more vanishing moments you must increase the size of wavelet. In our control application we found "Symlets" or "Daubechies" of order 4 or more were found to be a reasonably good.

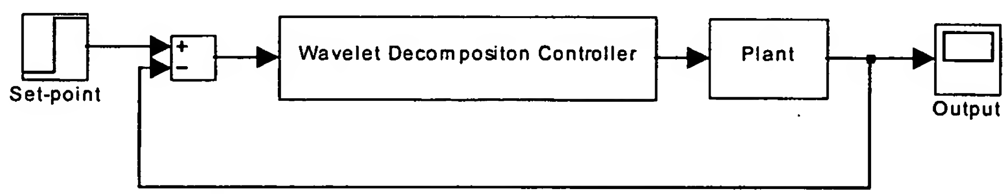

FIG 1. BLOCK DIAGRAM OF A PLANT USING WAVELET CONTROLLER

All physical systems are subjected to some types of extraneous signals or noise during operation. Therefore, in the design of a control system, consideration should be given so that the system is insensitive to noise and disturbance. The effect of feedback on noise and disturbance greatly depends on where these extraneous signals occur in the system. But in many situations, feedback can reduce the effect of noise and disturbance on the system performance. In practice disturbance and commands are often low-frequency signals, whereas sensor noises are often high-frequency signals. This makes it difficult to minimize the effect of these uncertainties simultaneously. It is under these conditions that WC performs extremely well. For a plant corrupted with high amount of measurement noise, WC can be used to generate low and high frequency components and then as noise has high frequency content of the error signal, gain corresponding to the high frequency component is set to zero. In a similar way higher gains have to be assigned to the lower frequency components of the WC in order to increase the disturbance rejection of the plant. Simulation results shown in the section 4 reflect these properties of the Wavelet Controller.

4. SIMULATION RESULTS

Simulations were run on different types of plants, however, in order to show the versatility of the Wavelet Controller simulation results on two examples from different

areas of control shown. First is a motion control plant and second is a temperature control plant.

4.1 MOTION CONTROL PROBLEM

A motion control problem involving low-frequency mechanical resonance in industrial servo system is chosen. Standard servo control laws are structured for rigidly-coupled loads. However, in practical machines some compliance is always present; this compliance often reduces control-loop stability margins, forcing servo gains down, which reduces machine performance. Often, the resulting rigidity of the transmission is so low that instability results when control-law gains are raised to levels necessary to achieve the desired servo performance. The well-known lumped-parameter model [5] for a compliant coupling is shown in Fig. 2.

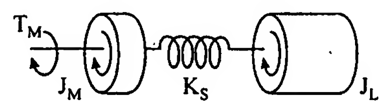

FIG. 2. SIMPLE COMPLIANTLY-COUPLED MOTOR AND LOAD

A schematic diagram of the compliantly coupled mechanism of Fig.2 is shown in Fig 3. Here, the equivalent spring constant of the entire transmission is K_S; also, to represent loss-producing properties, a mechanical damping term is shown producing torque in proportion to velocity differences via cross-coupled viscous damping, b_s.

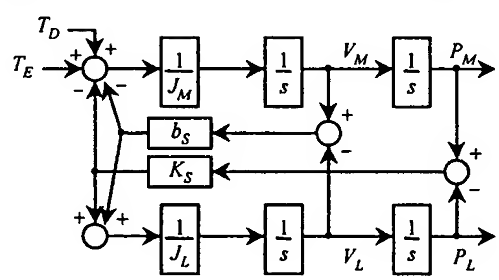

FIG. 3. BLOCK DIAGRAM OF A COMPLIANTLY-COUPLED LOAD

The transfer function from electromechanical torque T_E, to motor velocity, V_M, is

$$\frac{V_M}{T_E} = \frac{1}{J_M + J_L} \frac{1}{s} \frac{J_L s^2 + b_s s + K_S}{\frac{J_L J_M}{J_L + J_M} s^2 + b_s s + K_S} \qquad (7)$$

Which is a single, lumped inertia, $1/[(J_M+J_L)]s$, modified by a bi-linear quadratic or "bi-quad" function. The bi-quad term has its minimum gain at F_{AR} and maximum at F_R as shown in Eq. (8).

$$F_{AR} = \frac{1}{2\pi}\sqrt{\frac{K_S}{J_L}} \text{ Hz}$$

$$F_R = \frac{1}{2\pi}\sqrt{\frac{K_S}{\left(\frac{J_L J_M}{J_L + J_M}\right)}}\ \text{Hz} \qquad (8)$$

The bi-quad corrupts the plant at and above the anti-resonant frequency, F_{AR}. The key problem presented by a compliant coupling for low-frequency resonance [6] is the net increase in gain above the resonant frequency, F_R.

The wavelet controller discussed in section 3 was used to control the velocity of the resonant plant. 3-level decomposition of the error signal was done resulting in a high scale, low scale and two intermediate scale signals. Each of these signals were scaled by their respective gains and added to compute the control signal. Comparison of simulation results for a Proportional-Integral (PI) controller and a WC are shown in Fig. 4. It can be

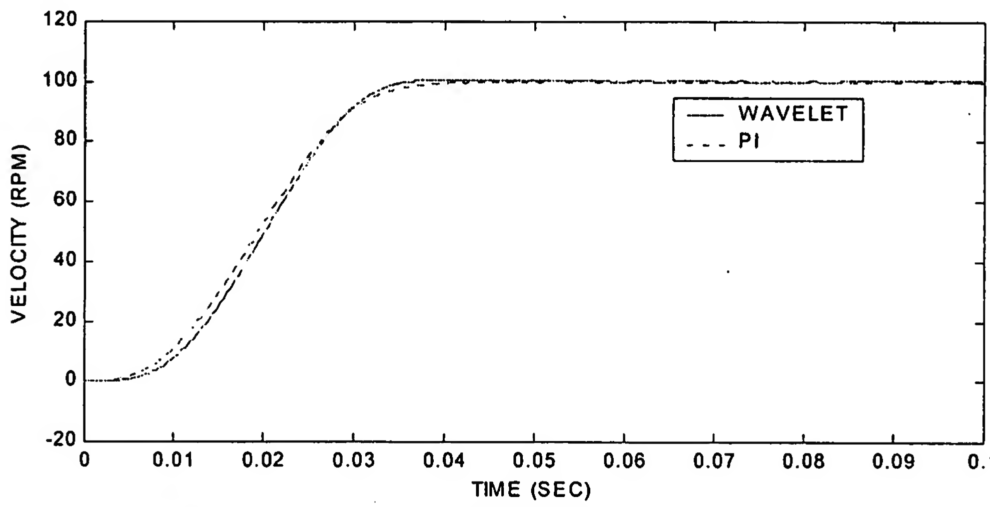

FIG 4. SIMULATION RESULTS USING A WAVELET CONTROLLER

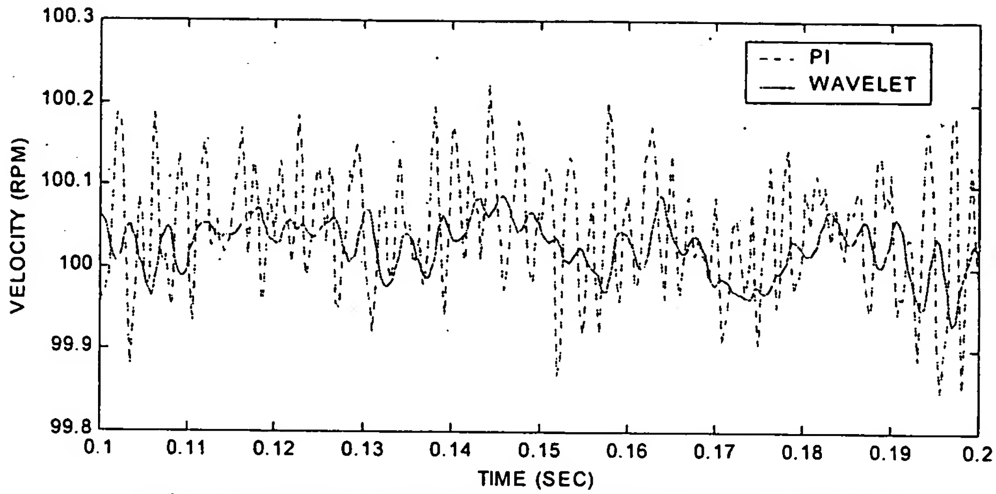

FIG 5. EFFECT OF NOISE DURING STEADY STATE

seen that WC performs slightly better than a PID, however it performs much better noise rejection as can be seen from Fig. 5. Noise is an important factor that effects control system performance. It is a well established fact that noise restricts the bandwidth of the control system and reduces system stability. Therefore using a wavelet controller offers distinct advantage of improving system bandwidth and stability.

4.2 TEMPERATURE REGULATION PROBLEM

Consider a generic temperature control application. Hot and cold fluids are mixed in a mixing valve, and the fluid is supplied through a supply line to a tank at a distance. The temperature is measured by a suitable sensor such as Thermocouple, Thermistor, etc., and converted to a signal acceptable to the controller. The controller compares the temperature signal to the desired set-point temperature and actuates the control element. The control element alters the manipulated variable to change the quantity of heat being added to or taken from the process. The objective of the controller is to regulate the temperature as close as possible to the set point. In this simulation test, hot and cold water are manipulated variable and a valve is the controller element. One of the difficulties with this system is the wide range of temperatures at which the system is operated, and also the variable time delays. The simplified block diagram of the temperature control problem is shown in figure 6. C(s) represents the controller and $G(s)e^{-s\tau}$ represents the plant with a pure time delay of τ. It is well known that time delays make the temperature loops hard to tune. The transfer function for the tank temperature control problem is given by [7]

$$G(s) = \frac{e^{-s\tau}}{s/a + 1} \tag{9}$$

Where, τ is the time delay for material transport in the pipe, $a = \dot{m}/M$, $\dot{m}$ = mass flow rate, and M= Fluid mass contained in the tank. More details of the problem can be found in [7].

The simulation block diagram of the plant using a wavelet controller is shown in Fig.6. Figures 7(a) shows the response of PID and wavelet transform based controller for

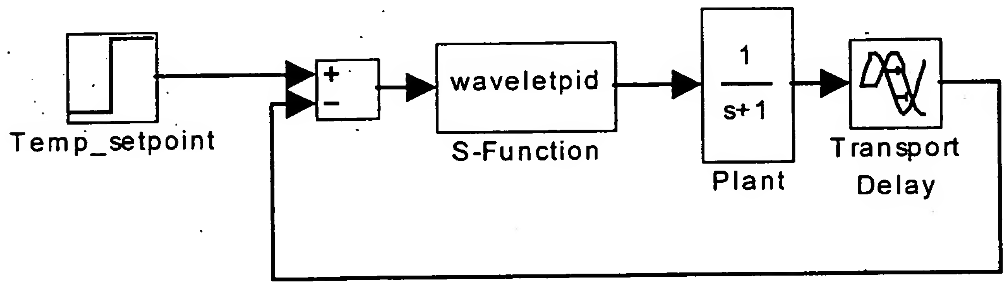

FIG 6. SIMULATION DIAGRAM OF A TEMPERATURE REGULATION PROBLEM

variable delays with plant parameter a=1. Both controllers are each tuned for a delay of 5 seconds and then the delay is changed from 5 seconds to 7 seconds. Effect of this change is seen in Figure 7(b). The results for temperature regulation plant are shown in order to validate the scheme of the wavelet controller and extend its applicability to different industrial processes. Once again it can be seen that WC performs slightly better than a PID in terms of transient and steady state response, however it gives us an alternative framework to control a system. Furthermore, it has an edge over the PID when it comes to disturbance rejection and de-noising as seen in section 4.1.

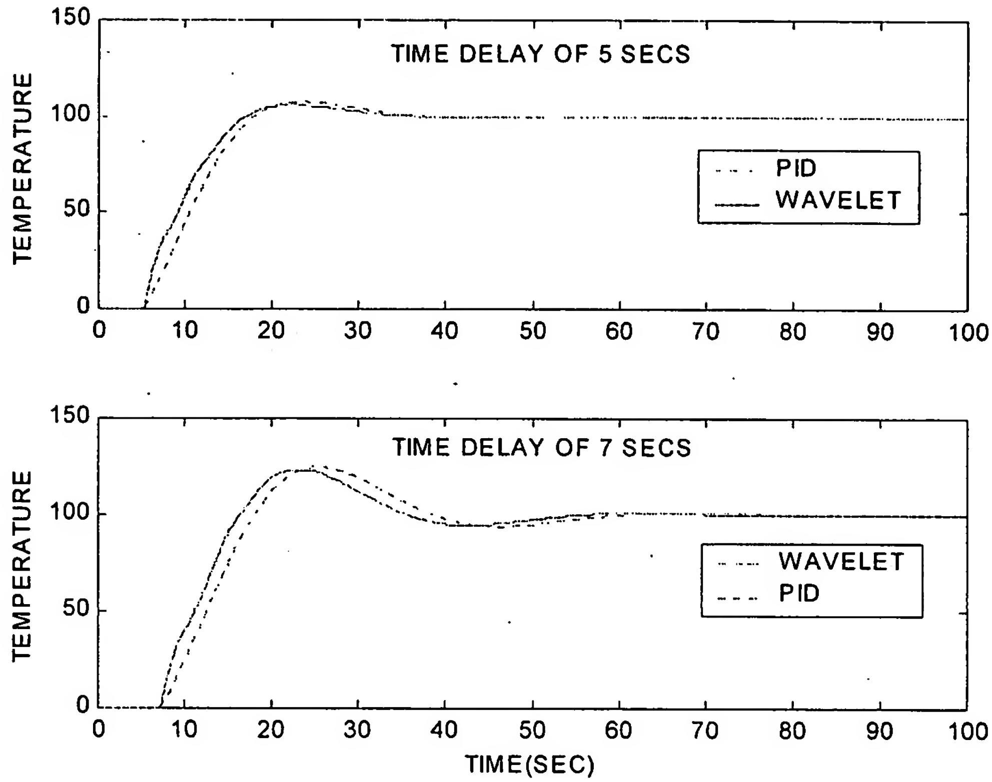

FIG 7 (A) & (B) SIMULATION RESPONSE OF A TEMPERATURE REGULATION PLANT FOR DIFFERENT TIME DELAYS

4.3 GUIDELINES FOR CONTROLLER DESIGN

Just like a PID the wavelet controller gains have a physical relationship with the control system performance characteristics. Following points may be used when designing or tuning a wavelet controller:

1. "Symlets" or "Daubechies" of order 4 or more were found to be a reasonably good tool for control.
2. Since wavelet analysis is a windowing technique it works on finite-length zero-order-hold signals. Length of the signal used during analysis is an important factor that can affect the performance of the controller. It was found that the length of the buffer corresponding to the error signal was to be no less than 2*order of wavelets* No. of decomposition levels. And in most cases 3-level decomposition yielding 4 signals was found to be sufficient.
3. Sum of the detailed waveforms approximately corresponds to the differentiation of the signal.
4. A major advantage with this controller is the low gain associated with computation of the differentiation of the signal.

5. In order to have better noise rejection, gains corresponding to low level detailed signals (D) have to be set to zero.
6. In order to improve disturbance rejection gain corresponding to the approximate signal has to be increased.
7. Steady state error in most plants reduced to less than .2% and in case of a plant of type 1 or more (with one or more pole at zero) the steady state error goes to zero.

5 CONCLUSIONS

A controller analogous to a PID using wavelet transforms is proposed. Just like a PID the wavelet controller gains have a physical relationship with the control system performance characteristics, which makes the tuning very easy. The wavelet decomposition, which represents the error signal at different scales, enables us to compensate for uncertainties in plant in the control design. Implementation of the wavelet controller in hardware is in progress.

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AUTHOR INDEX

ISA | ISA EXPO 2002 (Archive)

ISA 2002 Archive

Held 21-24 October
Chicago, IL, USA

Industry Rallies around ISA 2002
Participants Cite ISA 2002 as Seminal Event for Instrumentation, Systems, and Automation

Research Triangle Park, 11 November 2002 - The Instrumentation, Systems, and Automation Society announced its most successful annual conference, exhibition, and training event since 1998. "Given the struggling world economy, continued compression of the players in controls and automation, and the increasing number of conferences and exhibitions vying for attention, ISA 2002 stands as the most important forum for instrumentation, systems, and automation professionals and the companies that serve them," said Michael Jost, PhD, vice president, Foxboro Measurement and Instrumentation Division of Invensys.

Held in Chicago 21-24 October, ISA 2002 featured a unique combination of daily keynotes, special forums, conference sessions, hands-on training classes, and product displays. Truly an international event, ISA 2002 saw attendees from more than 70 countries and 50 exhibitors from companies outside the U.S., in addition to the Chile and Korea Pavilions. Another important part of ISA 2002 was the 10^{th} Annual International Temperature Symposium, co-sponsored by NIST and ISA and run in tandem with the ISA conference. This once-a-decade event added even more depth to the rich opportunity for executive dialogue and exposure to new products offered throughout the week.

The ISA Honors and Awards Banquet on Sunday, 20 October, set an upbeat tone, when Life Achievement Award recipient John Berra, president of Emerson Process Management, told several hundred instrumentation, systems, and automation professionals, "You are the backbone of the process industries. You have tremendous impact on the companies that employ you." National Instruments chairman, president, and CEO Dr. James Truchard, in accepting honorary membership in ISA, noted, "As technology such as virtual instruments and Internet-based controls become pervasive, organizations like ISA play a key role."

This year ISA expanded its conference programming to include several forums free to all attendees. The most popular of the forums was "Dick's Last Retort," moderated by Dick Morley, known as the "father of the PLC." Attended by more than 500 individuals, the first-time session offered a no-holds-barred panel discussion where industry insiders and top executives examined the future of automation.

While there were fewer large, corporate stands than in previous ISA exhibitions, the instrumentation, systems, and automation community was represented in full force. "All the players were there," said Alan Erickson, P.E., senior instrumentation & controls engineer with Bibb and Associates. "From Microsoft to Siemens to OPC and HART, everyone who is anyone was at the show. The ISA show was a great opportunity to network with other professionals. It really helped me with a couple of projects I

have going on right now."

"I want to be able to see all the offerings that are out there and review and compare the options," said Walter Anderson, instrument and electrical maintenance manager with a subsidiary of PCS Nitrogen. "Then I like to talk with the companies about their product plans, where they're planning to go. My company isn't going to send me to multiple shows every year. I had pretty much one opportunity, and I chose ISA. If a company didn't come to ISA, it would be hard for me to consider them in my buying plans."

"ISA 2002 was probably one of the most successful events for CyboSoft," said exhibitor George Cheng, Ph.D., Cybosoft chairman and CTO. "Those attending were decision-makers. So, we had the opportunity to spend quality time with people who were seriously looking for solutions. Plus, it was a wonderful opportunity to meet many international visitors."

Jan Kapushinsky, marketing communication manager for ASCO Valve, Inc. added, "ISA 2002 was an exciting show for ASCO. We introduced a new technology to our RedHat line of solenoid valves, and it was accepted with great
enthusiasm. We tried some new promotional efforts this year to bring our customers and users of our products to this show, who might not normally come, and it paid off for us as well as for other exhibitors."

"It was amazing how busy we were, especially the first day. We came home with very good, positive leads that will bring future business opportunities," commented Regina VanBrunt, trade show manager for Tyco Thermal Controls. "We are totally thrilled and have already signed up for next year in Houston

Given the changing nature of the trade event industry, the ISA leadership decided to eliminate one day of the conference and exhibition next year. ISA EXPO/2003 will move to a Tuesday through Thursday schedule, taking place 21-23 October 2003, at the new Reliant Center, Houston, Texas. For information about ISA EXPO/2003, contact ISA at (919) 549-8411 or info@isa.org.